NACA

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE

ROTOR BLADE TEMPERATURES IN A TURBOJET ENGINE

OPERATING AT TURBINE-INLET TEMPERATURES UP TO

2580° R AND ALTITUDES OF 50,000 AND 60,000 FEET

By Henry O. Slone, Reeves P. Cochran, and Robert P. Dengler

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

August 20, 1956
Declassified February 10, 1959

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE ROTOR BLADE TEMPERA-

TURES IN A TURBOJET ENGINE OPERATING AT TURBINE-INLET TEMPERATURES UP

TO 2580° R AND ALTITUDES OF 50,000 AND 60,000 FEET

By Henry O. Slone, Reeves P. Cochran, and Robert P. Dengler

SUMMARY

Temperature data for air-cooled turbine rotor blades were obtained during an experimental investigation conducted in an altitude test chamber to determine some of the problems pertinent to the operation of air-cooled turbojet engines at turbine-inlet temperatures from about 2200° to 2580° R. The test engine was a production-model turbojet engine modified with air-cooled turbine stator and rotor assemblies. The rotor blades were fabricated from a noncritical metal, and the stator blades were fabricated from a high-temperature alloy. Both rotor and stator blades were of the corrugated-insert type. Sources of air external to the engine were used for cooling the rotor and stator blades.

The rotor blade temperature data were obtained over a range of turbine-inlet temperatures from approximately 2200° to 2580° R, at altitudes of 50,000 and 60,000 feet, and at a simulated flight Mach number of 0.8. Laboratory service air having rotor blade-inlet cooling-air temperatures varying from about 600° to 700° R was used to cool the rotor blades at a turbine-inlet temperature of 2200° R. For turbine-inlet temperatures above 2200° R, the rotor blade cooling air was refrigerated to keep the temperature of the noncritical rotor blades in a safe range. With this refrigerated air supply the rotor blade-inlet cooling-air temperature varied from about 400° to 600° R. Laboratory service air was used to cool the stator blades for all test conditions.

A change in altitude from 50,000 to 60,000 feet indicated an increase in the required cooling-air flow ratio of about 30 percent for a turbine-inlet temperature of about 2270° R and an average rotor blade temperature of 1360° R. A reduction in the blade-inlet cooling-air temperature of 230° R, resulted in a drop in the average rotor blade temperature of 140° R for a required cooling-air flow ratio of 0.05, a turbine-inlet temperature of about 2200° R, and an altitude of 50,000 feet.

Comparisons of analytically determined average blade temperatures and experimentally obtained values showed different agreements and trends depending on the coolant flow regime considered. No definite conclusions could be drawn from these comparisons, however, because of the limited quantity of experimental data available.

INTRODUCTION

Up to the present time, no experimental temperature data for air-cooled turbine rotor blades were available for turbojet engines operating at high turbine-inlet temperatures and high altitudes. As part of an investigation to observe the problems encountered in the operation of an experimental air-cooled turbojet engine at turbine-inlet temperatures from about 2200° to 2580° R (ref. 1), air-cooled turbine rotor blade temperature data were recorded. The engine of reference 1 was operated at altitudes of 50,000 and 60,000 feet at a simulated flight Mach number of 0.8 in an NACA altitude test chamber. Thus, the investigation of reference 1 affords the opportunity of examining experimental turbine rotor blade heat-transfer data for high turbine-inlet temperatures and high altitudes. In addition, the experimental rotor blade temperature data may be used to substantiate the equations and methods (refs. 2 and 3) used to determine analytically air-cooled rotor blade temperatures in gas-turbine engines operating at high turbine-inlet temperatures and high altitudes.

Most of the NACA experimental and analytical turbine cooling research up to 1955 is summarized in reference 4. Experimental air-cooled turbine rotor blade temperatures have been obtained for a number of internal-cooling configurations. These temperature data were obtained at turbine-inlet temperatures of about 2000° R and sea-level static conditions. In some cases, comparisons of experimental and analytical blade temperatures were made (refs. 4 and 5). These comparisons were fairly successful and gave encouragement to using the analytical methods for predicting turbine blade temperatures or cooling requirements for conditions other than sea-level static and a turbine-inlet temperature of about 2000° R.

The engine used in the present investigation (see ref. 1) was a production-model turbojet engine modified with air-cooled stator and rotor assemblies. The test engine was assembled from a number of available parts that were not ideal for an investigation at high turbine-inlet temperatures, but as pointed out in reference 1, they did serve as a research expedient. The rotor blades were fabricated from noncritical metals and the stator blades were fabricated from a high-temperature alloy. Both rotor and stator blades were of the corrugated-insert type. Sources of air external to the engine were used for cooling the rotor and stator blades. Laboratory service air having rotor blade-inlet cooling-air temperatures varying from about 600° to 700° R was used to

cool the rotor blades at a turbine-inlet temperature of 2200° R. For turbine-inlet temperatures above 2200° R, the rotor blade cooling air was refrigerated to keep the temperature of the noncritical rotor blades in a safe range. With this refrigerated air supply the rotor blade-inlet cooling-air temperature varied from about 400° to 600° R. Laboratory service air was used to cool the stator blades for all test conditions.

The purpose of this report is to present turbine rotor blade temperature data over a range of ratios of cooling-air to combustion-gas flow for turbine-inlet temperatures from about 2200° to 2580° R and altitudes of 50,000 and 60,000 feet at a simulated flight Mach number of 0.8. In order to substantiate equations and methods used to predict cooled blade temperatures, a comparison is made between analytically determined average rotor blade temperatures and the averaged experimental blade temperatures.

APPARATUS AND INSTRUMENTATION

Engine

A modified production-model axial-flow-compressor turbojet engine was installed in the NACA Lewis 10-foot-diameter altitude test chamber. (The test chamber is described in ref. 6.) The modifications to the engine consisted of special combustor sections, air-cooled turbine stator and rotor assemblies, and an altered tailcone in place of the standard engine parts. A schematic sketch of the engine is shown in figure 1 and a more detailed description of the engine is given in reference 1.

As pointed out in reference 1, the engine used in the present investigation was assembled from a number of available parts which were not originally designed as mating parts. The air-cooled turbine rotor assembly was the same split-disk rotor with noncritical corrugated-insert blades that is described in detail in reference 7. A photograph of the noncritical air-cooled corrugated-insert rotor blade used herein is shown in figure 2. Reference 7 states that excessive quantities of Nicrobraz present in the shell-to-base joint during the fabrication of the blades used in this investigation caused clogging of a considerable number of coolant passages within the blade base. The two rotor blades instrumented for this investigation were chosen because their coolant passages were fairly free of clogging by braze material. Either laboratory service air or refrigerated air from sources external to the engine could be used to cool the turbine rotor blades (see fig. 1). A more detailed description of the turbine rotor assembly and its cooling-air supply system is given in references 1 and 7. The stator blades were fabricated from a high-temperature alloy, N-155, and were corrugated-insert blades. Reference 1

describes the stator blades in detail. Laboratory service air was used to cool the stator blades for all of the test conditions.

Instrumentation

The turbine rotor blade temperatures were measured on two blades located diametrically opposite each other. The temperatures were read by means of thermocouples installed at the one-third-span position. One blade (blade I) was instrumented as shown in figure 3, and the other blade (blade II) had thermocouples at corresponding leading- and trailing-edge positions only. The thermocouples located in the base of blade I measured the temperature of the cooling air entering the base, and the other thermocouples measured blade shell temperatures. In addition to the rotor blade instrumentation, temperatures were measured on the turbine rotor disk and the cooled stator blades (see ref. 1). A rotating thermocouple slipring (fig. 1) was used to transfer all rotating temperature readings to recording instruments.

Air-flow and gas-flow conditions were recorded at stations 1, 2, 3, 6, and 7 (fig. 1) by means of thermocouples and pressure tubes. The engine-inlet air weight flow was measured at station 1 by a calibrated venturi tube, and the rotor blade cooling-air weight flow was obtained at station 7 by means of static-pressure taps, an integrating total-pressure tube, and a thermocouple.

PROCEDURE

The investigation of reference 1 to determine some of the problems pertinent to the operation of air-cooled gas-turbine engines at turbine-inlet temperatures in excess of 2200° R was divided into two phases. It was only during the first phase of the investigation wherein the turbine-inlet temperature was varied from about 2200° to 2580° R at altitudes of 50,000 and 60,000 feet that the turbine rotor temperature data reported herein were obtained. During this phase of the investigation the ratio of turbine rotor blade cooling-air to combustion-gas flow (hereinafter referred to as the cooling-air flow ratio) was varied at each setting of turbine-inlet temperature. Both the turbine rotor and stator blades were supplied with a high value of cooling-air weight flow prior to starting the engine. Then the engine was brought up to its maximum speed at predetermined values of altitude, simulated flight Mach number, and turbine-inlet temperature, with the exhaust nozzle fully open. Because of limiting loading on the turbine (a condition where further increase in turbine pressure ratio results in no increase in turbine work output), the maximum engine speed obtained in these tests was about 90 percent of the rated corrected speed of 7950 rpm. After data were recorded at the initial operating conditions, the engine was operated over a range of

cooling-air flow ratios by successively reducing the cooling-air flow while the other operating conditions were maintained constant. Turbine rotor blade temperature data were recorded at each of these cooling-air flow ratios. As the cooling-air flow ratio was reduced, the turbine work required to pump the cooling air through the blades was reduced. In order to maintain the initial engine speed and turbine-inlet temperature as the cooling-air flow ratio was decreased, it was necessary to close the exhaust nozzle, thereby decreasing the turbine pressure ratio and thus the turbine work.

At a turbine-inlet temperature of about 2200° R the turbine rotor blades were cooled with both laboratory service air and refrigerated air in separate operations. The cooling-air temperature at the rotor blade-inlet varied from about 600° to 700° R when the service air was used. The use of refrigerated air to cool the turbine rotor blades over the range of turbine-inlet temperatures considered herein (2200° to 2580° R) resulted in a variation in rotor blade-inlet cooling-air temperatures from about 400° to 660° R for a range of cooling-air flow ratios from 0.114 to 0.020. The rotor blade-inlet cooling-air temperature was taken as the average of the temperature readings (these readings were almost identical) obtained from the two thermocouples located in the base of blade I (see fig. 3). This average cooling-air temperature was also taken as the effective cooling-air temperature at the rotor blade inlet. At no time during the tests was the rotor blade average temperature permitted to exceed a value of about 1500° R. This temperature was assumed to be a safe limiting value for the rotor blade used. A discussion of how this average blade temperature was obtained follows in the section Local Blade Temperatures.

During the entire investigation laboratory service air was supplied to the stator blades. The cooling-air weight flow to the stator blades was maintained at the maximum quantity permissible with the available supply system. As stated in reference 1, there was a severe leakage of the cooling air at the root of the stator blades due to a differential expansion between the inner and outer radius of the stator assembly. This expansion caused the stator blades to separate from the cooling-air manifold at the inner radius, thus allowing the cooling air to leak into the gas stream before reaching the stator blades. Because of this leakage, the quantity of cooling air passing through the stator blades could not be determined accurately. Also, between test conditions, adjustments were made to the stator throat area in an effort to reach rated mechanical speed or keep the compressor out of surge. Although these area adjustments were slight, there was a definite variation in stator throat area between the initial and final test conditions. No attempt was made to correct the gas conditions around the turbine rotor blades for the two possible sources of error just discussed because of the unknown extent of their influence.

A summary of calculated average turbine-inlet temperatures, alti-
tudes, average corrected engine speeds (corrected for compressor-inlet
conditions), ranges of blade-inlet cooling-air temperatures, and ranges
of cooling-air flow ratios covered in this investigation is given in the
following table:

Calculated aver-age turbine-inlet temperature, ^{o}R	Altitude, ft	Average cor-rected en-gine speed, rpm	Range of rotor blade-inlet cooling-air temperature, ^{o}R	Range of cooling-air flow ratio
2200	50,000	6970	430 to 710	0.032 to 0.080
2260	50,000	7100	450 to 640	.020 to .052
2270	60,000	6830	450 to 605	.036 to .077
2380	60,000	6760	424 to 660	.031 to .102
2580	60,000	6820	400 to 470	.070 to .114

The average values of turbine-inlet temperature and corrected engine
speed are the averages of the individual values calculated or obtained
over the range of cooling-air flow ratios. The turbine-inlet temperature
was calculated by the method presented in reference 8.

All symbols used in this report are defined in appendix A. The
methods used to determine the analytical average blade temperatures are
presented in appendix B.

RESULTS AND DISCUSSION

The following sections present the results of an experimental in-
vestigation wherein blade temperatures were obtained for corrugated-
insert rotor blades used in a modified air-cooled turbojet engine. The
engine was operated at turbine-inlet temperatures varying from about
2200° to 2580° R and altitudes of 50,000 and 60,000 feet at a simulated
flight Mach number of 0.8.

Local Blade Temperatures

Figure 4 shows a plot of the six local blade temperatures obtained
from blades I and II against cooling-air flow ratio for a turbine-inlet
temperature of 2580° R and an altitude of 60,000 feet. In addition, for
these operating conditions, the blade-inlet cooling-air temperature
(average of the two temperature readings obtained in the base of blade I)
is shown. The results shown in figure 4 are typical of those obtained
at the lower turbine-inlet temperatures.

    The variations in rotor blade-inlet cooling-air temperature indicated on figure 4 were due to heat picked up by the cooling air as it was ducted to the rotor blades (fig. 1). Thus, for a given turbine-inlet temperature, as the cooling-air flow ratio is decreased, the temperature rise of the cooling air in the ducting system is increased. The highest local blade temperatures recorded for the test conditions of figure 4 were about 1900° R at the leading edge of blade II and 1735° R at the leading edge of blade I. These temperatures were read at a cooling-air flow ratio of about 0.07 and a blade-inlet cooling-air temperature of about 470° R.

    As shown in figure 4, the leading- and trailing-edge temperatures recorded for blade II are about 60° to 160° R higher than corresponding temperatures on blade I for the range of cooling-air flow ratios considered. The midchord pressure-surface temperature of blade I is about 370° R higher than the midchord suction-surface temperature, and about 60° R higher than the trailing-edge temperature. The difference in the midchord local temperatures on the pressure and suction surfaces would not normally be present in air-cooled blades. Even though blades I and II were selected for instrumenting because their coolant passages were relatively free of braze material (as discussed previously), it is possible that sections of the coolant passage supplying the leading and trailing edges of blade II and the midchord pressure surface of blade I were partially clogged with braze material. It is also possible that because of leakage of stator cooling air into the combustion gas stream or the fact that the turbine rotor and stator blades were not matched for this engine (ref. 1), the gas flow around the turbine rotor blades caused the local temperature levels shown in figure 4.

    In a comparison of the effects of turbine-inlet temperature and altitude on turbine rotor blade temperatures, or analytically determined values with experimental blade temperatures, it is believed that an average rotor blade temperature based on the following considerations will be fairly representative of what the turbine rotor blades undergo during the various operating conditions. Owing to the limited local temperature data available (four local temperatures from blade I and two from blade II) and the temperature variations shown in figure 4, it was not possible to adequately determine a rotor blade peripheral blade temperature distribution and thus obtain an integrated average blade temperature. Therefore, an arithmetic average rotor blade temperature was determined by first assuming that blade II has the same midchord local temperatures as blade I. Then, these two assumed temperatures were added to the six local experimental blade temperatures obtained from blades I and II and the sum was divided by 8. The resulting average rotor blade temperature is certainly adequate for comparing the effects of turbine-inlet temperature and altitude on rotor blade temperature. It is realized that an integrated average experimental temperature would be more desirable for the comparison of analytically determined and experimental average blade temperatures.

Effect of Blade-Inlet Cooling-Air Temperature on Average

Rotor Blade Temperature When Either Laboratory Service

or Refrigerated Air is Used for Cooling

Only at a turbine-inlet temperature of about 2200° R was it feasible to adequately cool the noncritical rotor blades with laboratory service air. For turbine-inlet temperatures above 2200° R, it was necessary to use refrigerated air for cooling the rotor blades. However, for comparison purposes, both laboratory service and refrigerated air were used to cool the rotor blades at a turbine-inlet temperature of about 2200° R and an altitude of 50,000 feet at a simulated flight Mach number of 0.8. Figure 5 presents average turbine rotor blade temperatures at the one-third-span position and blade-inlet cooling-air temperatures plotted against cooling-air flow ratio using both laboratory service and refrigerated air for the operating conditions just stated.

The blade temperature reductions due to use of refrigerated air at a turbine-inlet temperature of 2200° R are indicated on figure 5. For example, at a value of w_a/w_g of 0.05, a reduction in blade-inlet cooling-air temperature of about 230° R resulted in an average blade temperature reduction of about 140° R. Further effects and benefits due to reductions in blade-inlet cooling-air temperature are discussed subsequently.

Effect of Cooling-Air Flow on Average Rotor Blade Temperature

for a Range of Turbine-Inlet Temperatures

A plot of average turbine rotor blade temperature $T_{B,av}$ at the one-third-span position against w_a/w_g is shown in figure 6 for the range of engine operating conditions considered in this investigation. All values of $T_{B,av}$ plotted on figure 6 were obtained using refrigerated air for cooling. In general, the results shown on figure 6 are what would be expected from reductions in w_a/w_g or increases in turbine-inlet temperature or both. The effect of a change in altitude from 50,000 to 60,000 feet is clearly indicated. For example, at a value of w_a/w_g of 0.05, $T_{B,av}$ is 1220° R for an altitude of 50,000 feet and a turbine-inlet temperature of about 2260° R. At the same value of w_a/w_g and a turbine-inlet temperature of about 2270° R, $T_{B,av}$ is 1270° R at an altitude of 60,000 feet. Thus, all other conditions remaining approximately the same, an increase in altitude from 50,000 to 60,000 feet resulted in about a 50° R rise in average blade temperature. Or, looking

at the altitude effect another way, a change in altitude from 50,000 to 60,000 feet for a fixed value of $T_{B,av}$ of 1360° R resulted in an increase in w_a/w_g of about 30 percent. Because of the number of variables involved, there is no simple explanation for the effect of altitude on cooling-air flow requirements. These results agree, however, with the analytical study of reference 9 wherein for a given turbine-inlet temperature and flight Mach number, an increase in altitude resulted in an increase in the cooling-air flow requirements of a corrugated-insert blade.

Cooling-Air Flow Requirements

In the design of an air-cooled turbojet or turboprop engine, it is important to know the cooling-air flow requirements for a given air-cooled turbine blade configuration and given engine operating conditions. The required values of w_a/w_g are usually determined by specifying a limiting value of average blade temperature. (The value specified depends on the stress-rupture properties of the blade material, the blade stresses, and a suitable stress-ratio factor, as discussed in reference 5.) The required cooling-air flow ratios were obtained for the corrugated-insert blade used herein by cross-plotting figure 6. The results of this cross plot are shown in figure 7 for assigned values of $T_{B,av}$ of 1360° and 1460° R.

Figure 7 shows that the selection of a blade material (at the same stress level) has an important effect in determining the required cooling-air flow ratios. For example, if a turbine-inlet temperature of 2500° R and an altitude of 60,000 feet is selected, and $T_{B,av}$ can be increased from 1360° to 1460° R, a reduction in w_a/w_g of about 19 percent results (from 0.061 to 0.049) (fig. 7). Similar results were obtained at other values of turbine-inlet temperature and at an altitude of 50,000 feet.

Of course, it should be pointed out that reductions in w_a/w_g may also be obtained by improving the cooling effectiveness of a blade by changing the internal coolant passage configuration. Reference 5 gives an indication of the effect of coolant passage configuration on the cooling-air requirements of an air-cooled blade.

Once again, as in figure 6, the effect of a change in altitude from 50,000 to 60,000 feet is apparent in figure 7.

Blade Temperature Correlation

Equation (B1) of appendix B indicates the one-dimensional relation for the temperature difference ratio $\dfrac{(T_{g,e} - T_{B,av})}{(T_{g,e} - T_{a,e,h})}$.

If the exponential term in equation (B1) does not vary appreciably, the temperature difference ratio can be approximated as

$$\frac{T_{g,e} - T_{B,av}}{T_{g,e} - T_{a,e,h}} \approx \frac{constant}{1 + \lambda}$$

If the small effects of changes in the gas and cooling-air properties on the heat-transfer coefficients are neglected, it can be shown that

$$h_{o,av} \approx constant \; (w_g)^m$$

and

$$h_{f,av} \approx constant \; (w_a)^n$$

Thus,

$$\lambda \approx constant \; \frac{w_g^m}{w_a^n}$$

In some cases, the exponents m and n may be equal. On the basis of the preceding discussion, and with m assumed equal to n, the temperature-difference ratio becomes a function of the gas and cooling-air flows;

$$\frac{T_{g,e} - T_{B,av}}{T_{g,e} - T_{a,e,h}} \approx f(w_a/w_g)$$

Thus, a plot of the temperature-difference ratio against w_a/w_g might correlate average blade temperature data for various cooling-air and gas-temperature conditions.

Values of $(T_{g,e} - T_{B,av})/(T_{g,e} - T_{a,e,h})$ are plotted against w_a/w_g in figure 8 for all the temperature data presented in figures 5 and 6. The values of $T_{g,e}$ and $T_{a,e,h}$ were obtained by the methods discussed in appendix B, and they are the individual values obtained for each value of w_a/w_g.

In general, the temperature data of this investigation correlated rather well (fig. 8), in view of the variations in turbine-inlet temperature, blade-inlet cooling-air temperature, altitude, and corrected engine speed. From the results shown in figure 8, there are no apparent effects on the temperature-difference ratio due to changes in altitude, although altitude does affect $T_{B,av}$. Before any definite conclusion

can be drawn about the effects of altitude on a correlation such as that shown in figure 8, more information is required over a wider range of altitude. The results shown in figure 8 also indicate that the assumptions used in obtaining figure 8 are reasonable and that the temperature-difference ratio is probably insensitive to the assumption that the exponents m and n are equal. A close examination of figure 8 indicates that separate lines might be drawn through the data points which represent different turbine-inlet temperature levels. These lines, however, would be very close together. When one line is drawn through all of the points, as shown in figure 8, the scatter about this line is at most about ±6 percent, which is reasonable for any heat-transfer correlation. Thus, it appears that a straight line drawn through the data points of figure 8 may be used to evaluate average cooled rotor blade temperatures for turbine-inlet temperatures, blade-inlet cooling-air temperatures, and cooling-air flow ratios other than those covered in this investigation. Before the data of figure 8 can be used to evaluate $T_{B,av}$ at other altitude or flight Mach number conditions, more experimental information is required.

Effects of Reduction in Blade-Inlet Cooling-Air Temperature

on Average Blade Temperature

Reference 9 indicates that the required cooling-air flow ratio of a turbojet engine with supersonic capabilities may be reduced by reductions in the blade cooling-air supply temperature. As a matter of interest, figure 9 presents a plot of $T_{B,av}$ against $T_{a,e,h}$ for two values of turbine-inlet temperature and cooling-air flow ratio. The values shown in figure 9 were obtained by using the straight-line correlation of figure 8.

For a turbine-inlet temperature 2580° R and w_a/w_g equal to 0.025, a change in $T_{a,e,h}$ from 700° to 300° R results in a reduction in $T_{B,av}$ from 1595° to 1412° R. Conversely, if it is desired to limit $T_{B,av}$ to 1460° R, w_a/w_g can be reduced from 0.050 to 0.025 if $T_{a,e,h}$ is decreased from 610° to about 410° R for a turbine-inlet temperature of 2580° R (fig. 9). Similar changes are observed at the turbine-inlet temperature of 2200° R. Thus, as pointed out in reference 9 and shown in figure 9, large reductions in the required cooling-air flow ratio may be obtained by decreasing the blade-inlet cooling-air temperature. The methods that might be used to reduce the value of $T_{a,e,h}$ would probably include some type of heat-exchanger arrangement. The discussion of such methods, however, is beyond the scope of this report. Another fact pointed out by the results of figure 9 is that noncritical metals may be used for fabricating turbine rotor blades to operate at high turbine-inlet

temperatures if the blade coolant temperature is low enough. This situation could be helped considerably by having a coolant passage configuration with a better cooling effectiveness than the one used herein.

Comparison of Analytical and Experimental Average

Blade Temperatures

An effort was made to verify the use of the one-dimensional radial blade-temperature equation of reference 2 (eq. (B1)) by comparing theory and experiment on the basis of average blade temperatures over a range of cooling-air flow ratios. The calculation procedures and equations used for determining the analytical average blade temperatures are discussed in appendix B.

Figure 10 presents the comparison between analytical and experimental values of $T_{B,av}$ for turbine-inlet temperatures of 2580°, 2380°, and 2270° R. As pointed out in appendix B, two different methods were used to determine the blade-to-coolant heat-transfer coefficient. One method considers the coolant to be in the turbulent flow regime regardless of the Reynolds number (ref. 5). The other method considers turbulent flow to exist only above a Reynolds number of 8000, a transition region between Reynolds numbers of 8000 and 2000, and laminar flow below a Reynolds number of 2000 (ref. 3). The results shown in figure 10 cover a range of coolant Reynolds numbers from about 500 to 1400. The fluid properties in the Reynolds number are based on a film temperature, and the blade hydraulic diameter is the characteristic dimension.

It is interesting to note, in comparing figures 10(a), (b), and (c), how the agreement between experimental and analytical values of $T_{B,av}$ varies for the three turbine-inlet temperatures when considering only turbulent flow for the coolant. In figure 10(a), the analytical $T_{B,av}$ is about 20° lower than the experimental value, and the two curves are parallel. When the turbine-inlet temperature is reduced to 2380° R (fig. 10(b)), the analytical $T_{B,av}$ is slightly greater than the experimental values at the higher values of w_a/w_g. As w_a/w_g is reduced (fig. 10(b)), the spread between the analytical and experimental values of $T_{B,av}$ becomes quite significant for the case wherein only turbulent flow is considered for the coolant. A trend similar to that observed in figure 10(b) for the turbulent flow case is shown in figure 10(c).

The analytical values of $T_{B,av}$ determined by the method which considers a change in the coolant flow regime depending on the Reynolds number appear to have fairly consistent trends (fig. 10). At high values of

w_a/w_g, the analytical $T_{B,av}$ is about 100° higher than the experimental values. As w_a/w_g is reduced, the analytical and experimental values of $T_{B,av}$ tend to approach each other so that the agreement between the two is very good.

Comparison of figures 10(b) and (c) shows that the two analytical curves intersect each other at a value of w_a/w_g of about 0.05. If the two analytical curves in figure 10(a) were extrapolated, the intersection would occur at about the same value of w_a/w_g as in figures 10(b) and (c). It appears that if a combination of the two analytical curves were used, one analytical curve having good agreement with the experimental curve would be obtained. In order to study the curves of figure 10 further, the blade temperatures were plotted against Reynolds number instead of w_a/w_g. The intersection of the two analytical curves occurs at a Reynolds number of about 700.

From the preceding discussion, one may conclude that turbulent flow certainly exists for the coolant for Reynolds numbers above or equal to 8000. Turbulent flow may also exist for Reynolds numbers as low as 700 for the air-cooled rotor blade tested herein. It is possible, therefore, that the heat-transfer correlation curve of reference 3 which includes turbulent, transition, and laminar flow is not adequate for rotating air-cooled blades. That is, the correlation curve was obtained statically for corrugated shapes. Possibly, because of rotation, the turbulent flow regime is extended to Reynolds numbers below the 8000 limit indicated in reference 3.

All of the preceding discussion concerning comparisons between analytical and experimental average blade temperatures cannot be accepted completely until many more comparisons are made over a wide range of operating conditions and for other cooled blade configurations.

SUMMARY OF RESULTS

The following heat-transfer results were obtained in an investigation of an axial-flow turbojet engine equipped with an air-cooled turbine using corrugated-insert blades and operating at turbine-inlet temperatures up to 2580° R and altitudes of 50,000 and 60,000 feet at a simulated flight Mach number of 0.80:

1. At a turbine-inlet temperature of about 2200° R and an altitude of 50,000 feet, a reduction in the blade-inlet cooling-air temperature of 230° R resulted in a drop in the average rotor blade temperature at the one-third-span position of 140° R at a cooling-air flow ratio of 0.05.

2. For a turbine-inlet temperature of about 2270° R and a fixed average blade temperature of 1360° R, a change in altitude from 50,000 to 60,000 feet resulted in an increase in the required cooling-air flow ratio of about 30 percent.

3. Increasing the limiting average rotor blade temperature from 1360° to 1460° R for a turbine-inlet temperature of 2500° R and an altitude of 60,000 feet resulted in a reduction in the required cooling-air flow ratio from 0.061 to 0.049, a reduction of about 19 percent.

4. With the nondimensional temperature-difference ratio plotted against the cooling-air flow ratio, the temperature data of this investigation correlated rather well.

5. The required cooling-air flow ratio can be reduced from 0.050 to 0.025 for a turbine-inlet temperature of 2580° R and a limiting average blade temperature of 1460° R, if the blade-inlet cooling-air temperature can be decreased from 610° to about 410° R.

6. Comparisons of analytically determined average rotor blade temperatures and experimentally obtained values showed different agreements and trends depending on the coolant flow regime considered. No definite conclusions could be drawn from these comparisons, however, because of the limited quantity of experimental data available.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, March 28, 1956

APPENDIX A

SYMBOLS

a'_{cr} $\sqrt{\dfrac{2\gamma}{\gamma+1}\, gRT'}$, ft/sec

c_p specific heat at constant pressure, $Btu/(lb)(^{\circ}F)$

g acceleration due to gravity, $32.2\ ft/sec^2$

$h_{a,av}$ average blade-to-coolant heat-transfer coefficient, $Btu/(sec)(sq\ ft)(^{\circ}F)$

$h_{f,av}$ average effective inside heat-transfer coefficient, $Btu/(sec)(sq\ ft)(^{\circ}F)$

$h_{o,av}$ average gas-to-blade heat-transfer coefficient, $Btu/(sec)(sq\ ft)(^{\circ}F)$

k thermal conductivity, $Btu/(sec)(ft)(^{\circ}F)$

l blade perimeter, ft

m exponent

$Nu_{g,B}$ Nusselt number of gas, $\dfrac{h_{o,av}\, l_o/\pi}{k_B}$

n exponent

P static pressure, lb/sq ft abs

$Pr_{g,B}$ Prandtl number of gas, $c_{p,B}\, \mu_B\, g/k_B$

R gas constant, $53.4\ ft\text{-}lb/(lb)(^{\circ}R)$

$Re_{g,B}$ average Reynolds number of gas, $\dfrac{P_{av}W_{av}l_o/\pi}{\mu_B gRT_B}$

T temperature, $^{\circ}R$

T' total temperature, $^{\circ}R$

T"   relative total temperature, $^\circ R$

U_m mean blade velocity, ft/sec

V   absolute velocity, ft/sec

W   velocity relative to blade, ft/sec

w   weight flow, lb/sec

x   spanwise distance from blade root to any point on blade, ft

γ ratio of specific heats

λ $\dfrac{h_{o,av} l_o}{h_{f,av} l_i}$

μ viscosity, slugs/(sec)(ft)

Subscripts:

a   cooling air

av   average

B   blade, or based on blade temperature

e   effective

g   combustion gas

h   blade base

i   inside

o   outside

u   tangential component

APPENDIX B

CALCULATION PROCEDURE FOR DETERMINATION OF ANALYTICAL

AVERAGE BLADE TEMPERATURE

The equation which gives the one-dimensional radial average blade temperature distribution for an air-cooled turbine blade is stated and derived in reference 2 (eq. (18)). For the calculations considered herein, it was determined that the rotational terms of equation (18) were of minor importance, and they are neglected. (In some instances the rotational terms may become important, according to ref. 3, and they should not be neglected.) The one-dimensional equation without rotational terms is

$$\frac{T_{g,e} - T_{B,av}}{T_{g,e} - T_{a,e,h}} = \frac{1}{1 + \lambda} e^{-\left(\frac{1}{1+\lambda} \frac{h_{o,av}l_o x}{c_p w_a}\right)} \tag{B1}$$

where

$$\lambda = \frac{h_{o,av}l_o}{h_{f,av}l_i}$$

(Definitions of symbols are given in appendix A.) Before equation (B1) can be applied to determine the average blade temperature $T_{B,av}$ at a given spanwise position x, it is necessary that $T_{a,e,h}$, $T_{g,e}$, $h_{o,av}$, and $h_{f,av}$ be known. The effective cooling-air temperature at the blade base $T_{a,e,h}$ is taken as the average of the cooling-air temperatures from the thermocouples located in the base of the test blade (fig. 3). The methods of obtaining $T_{g,e}$, $h_{o,av}$, and $h_{f,av}$ are now discussed.

Effective Gas Temperature

The effective gas temperature $T_{g,e}$ was determined from figure 5 of reference 10, where for an assumed recovery factor of 0.89 and an average Mach number through the blade channel of 0.70 the following relation was obtained:

$$\frac{T_g'' - T_{g,e}}{T_g''} = 0.01 \tag{B2}$$

or

$$T_{g,e} = 0.99 \, T_g''$$ (B3)

A value of 0.70 for the Mach number is consistent with the turbine design of this investigation. The relative total gas temperature T_g'' was evaluated from the following equation of reference 11:

$$\frac{T_g''}{T_g'} = 1 - \frac{\gamma-1}{\gamma+1} \cdot \frac{U_m}{a_{cr}'} \left[2 \left(\frac{V_u}{a_{cr}'} \right) - \frac{U_m}{a_{cr}'} \right]$$ (B4)

wherein T_g', (V_u/a_{cr}'), and (U_m/a_{cr}') were evaluated at the turbine inlet. As pointed out previously, the turbine-inlet temperature was obtained by using the method of reference 8. The terms (V_u/a_{cr}') and (U_m/a_{cr}') were evaluated from the turbine velocity diagrams.

Gas-to-Blade Heat-Transfer Coefficient

The average gas-to-blade heat-transfer coefficient $h_{o,av}$ for the air-cooled corrugated-insert blades used in this investigation was obtained in reference 5 for sea-level static conditions. The blade considered herein is configuration H of profile 2 in reference 5. In order to obtain a value of $h_{o,av}$ at the temperature and altitude conditions of this investigation, the same heat-transfer correlation equation used in reference 5 was used. This correlation equation is

$$Nu_{g,B} = 0.14 \left(Re_{g,B} \right)^{0.662} \left(Pr_{g,B} \right)^{1/3}$$

In using this correlation equation, it was assumed that the velocity distribution around the blade was unchanged in going from sea-level to altitude conditions. Also, it was assumed that the correlation equation was unaffected by the mismatching of the stators and rotors or by changes in the stator throat area.

Effective Inside Heat-Transfer Coefficient

The average effective inside heat-transfer coefficient $h_{f,av}$ required in equation (B1) was obtained from figure 9 of reference 5 (for coolant passage configuration H). This figure is a plot of $h_{f,av}$ against the average blade-to-coolant heat-transfer coefficient $h_{a,av}$. For the present investigation, the value of $h_{a,av}$ was determined in

two different ways. In one case, $h_{a,av}$ was obtained by the method described in reference 5, which assumes that the coolant is in the turbulent flow regime. In the other case, $h_{a,av}$ was obtained from figure 2 of reference 3, wherein the coolant may be in the turbulent, transition, or laminar flow regimes, depending on the coolant Reynolds number. The fluid properties required in the evaluation of $h_{a,av}$ were based on the film temperature in accordance with reference 3.

REFERENCES

1. Cochran, Reeves P., Dengler, Robert P., and Esgar, Jack B.: Operation of an Experimental Air-Cooled Turbojet Engine at Turbine-Inlet Temperatures from 2200° to 2935° R. NACA RM E56D24a, 1956.

2. Livingood, John N. B., and Brown, W. Byron: Analysis of Spanwise Temperature Distribution in Three Types of Air-Cooled Turbine Blades. NACA Rep. 994, 1950. (Supersedes NACA RM's E7B11e and E7G30.)

3. Slone, Henry O., Hubbartt, James E., and Arne, Vernon L.: Method for Designing Corrugated Surfaces Having Maximum Cooling Effectiveness Within Pressure-Drop Limitations for Application to Cooled Turbine Blades. NACA RM E54H20, 1954.

4. Esgar, Jack B., and Ziemer, Robert R.: Review of Status, Methods, and Potentials of Gas-Turbine Air-Cooling. NACA RM E54I23, 1955.

5. Ziemer, Robert R., and Slone, Henry O.: Analytical Procedures for Rapid Selection of Coolant Passage Configurations for Air-Cooled Turbine Rotor Blades and for Evaluation of Heat-Transfer, Strength, and Pressure-Loss Characteristics. NACA RM E52G18, 1952.

6. Walker, Curtis L., Huntley, S. C., and Braithwaite, W. M.: Component and Over-All Performance Evaluation of an Axial-Flow Turbojet Engine over a Range of Engine-Inlet Reynolds Numbers. NACA RM E52B08, 1952.

7. Cochran, Reeves P., and Dengler, Robert P.: Static Sea-Level Performance of an Axial-Flow-Compressor Turbojet Engine with an Air-Cooled Turbine. NACA RM E54L28a, 1955.

8. Huntley, S. C.: Ideal Temperature Rise Due to Constant-Pressure Combustion of a JP-4 Fuel. NACA RM E55G27a, 1955.

9. Ziemer, Robert R., and Slone, Henry O.: Analysis of the Cooling-Air Requirements of Corrugated-Insert-Type Turbine Blades Suitable for a Supersonic Turbojet Engine. NACA RM E56B17, 1956.

10. Esgar, Jack B., and Lea, Alfred L.: Determination and Use of the
       Local Recovery Factor for Calculating the Effective Gas Tempera-
       ture for Turbine Blades. NACA RM E51G10, 1951.

11. Cavicchi, Richard H., and English, Robert E.: A Rapid Method for
       Use in Design of Turbines Within Specified Aerodynamic Limits.
       NACA TN 2905, 1953.

Station	Description
1	Inlet flow nozzle
2	Compressor inlet
3	Compressor discharge
4	Turbine inlet
5	Turbine discharge
6	Tailpipe
7	Turbine rotor blade cooling-air measuring station

Station 1   2   3   4   5   6

CD-4868

Rotating thermocouple sliprings

Laboratory service air supply for turbine stator cooling

Turbine stator cooling-air discharge

7

Refrigerated or laboratory service air for turbine rotor blade cooling
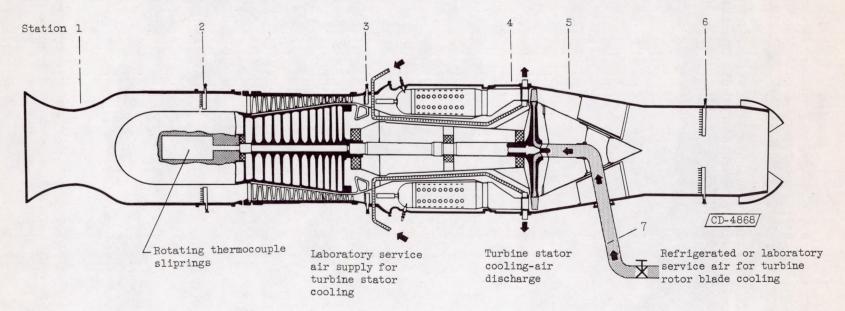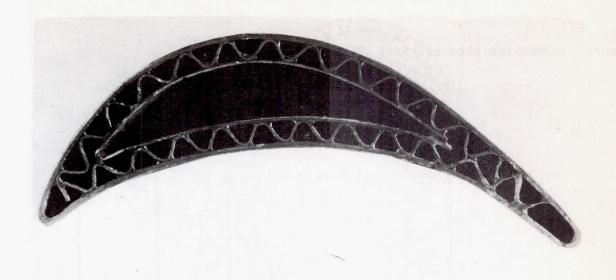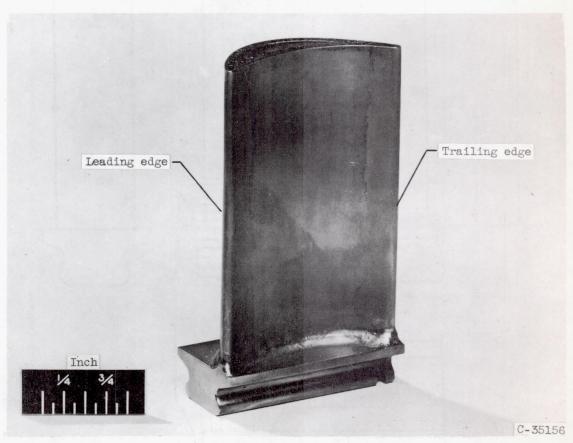
Figure 1. - Schematic diagram of production-model axial-flow-compressor turbojet engine modified for turbine cooling.

(a) Enlarged tip view.

Leading edge   Trailing edge

Inch
¼   ¾

C-35156

(b) Side view (pressure surface).

Figure 2. - Air-cooled corrugated-insert turbine rotor blade for modified engine.

4065
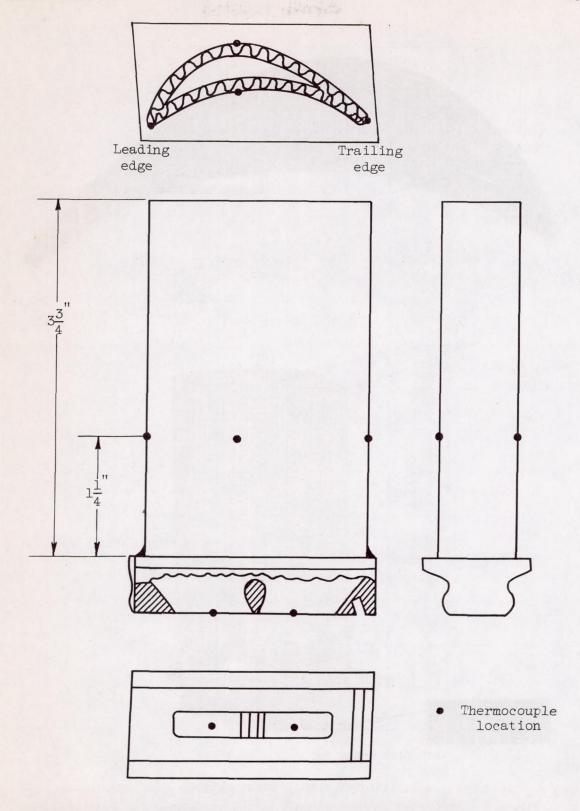
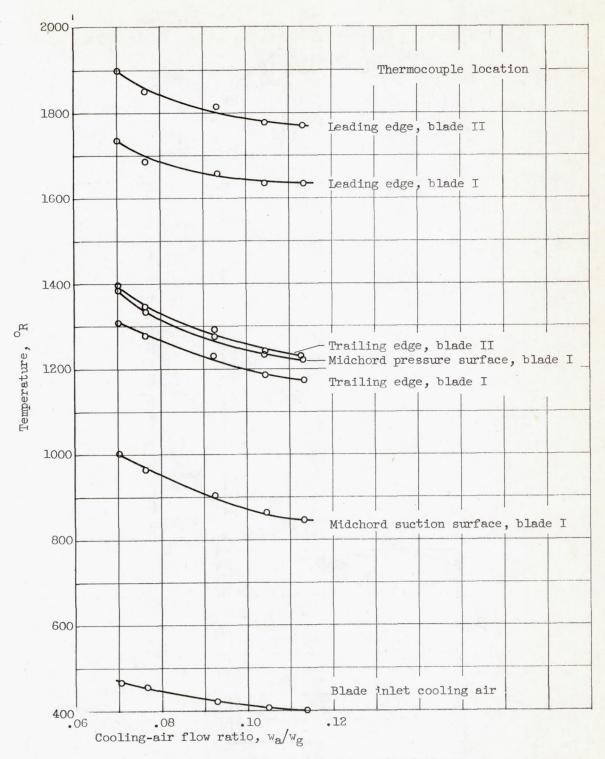
Figure 3. - Location of thermocouples on turbine rotor blade I.

Figure 4. - Variations in local turbine rotor blade temperatures at one-third span with cooling-air flow ratios. Turbine-inlet temperature, 2580° R; altitude, 60,000 feet; flight Mach number, 0.8.
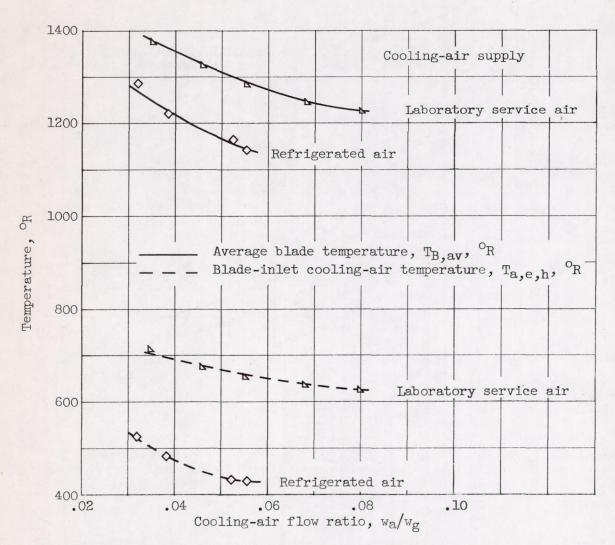
Figure 5. - Comparison of average rotor blade and cooling-air
temperatures when either laboratory service air or refrigerated
air is used for cooling. Turbine-inlet temperature, 2200° R;
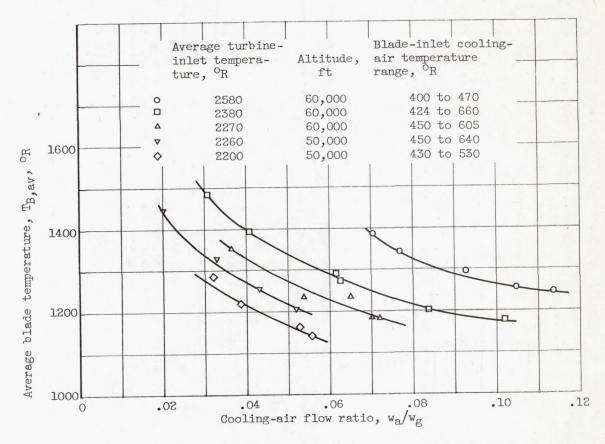altitude, 50,000 feet; flight Mach number, 0.8.

Figure 6. - Effect of cooling-air flow ratio on average turbine rotor
blade temperature at one-third span for altutudes of 50,000 and
60,000 feet and turbine-inlet temperatures ranging from 2200° to
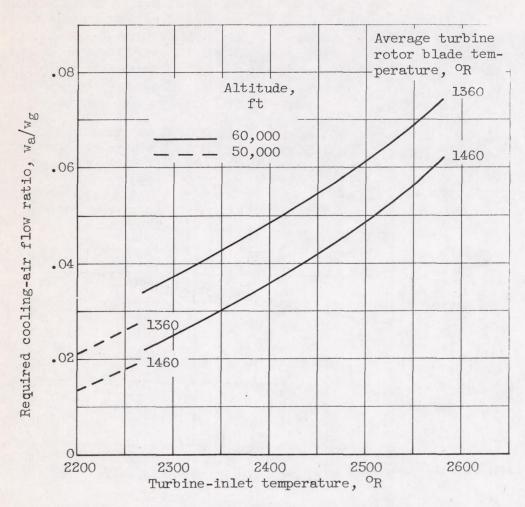2580° R. Flight Mach number, 0.8.

Figure 7. - Variations of cooling-air flow require-
ments with turbine-inlet temperature for two average
turbine rotor blade temperatures and altitudes.
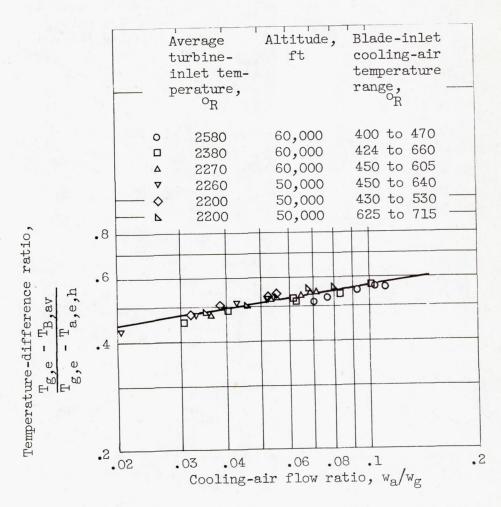Flight Mach number, 0.8.

	Average turbine-inlet temperature, ^{o}R	Altitude, ft	Blade-inlet cooling-air temperature range, ^{o}R
○	2580	60,000	400 to 470
□	2380	60,000	424 to 660
△	2270	60,000	450 to 605
▽	2260	50,000	450 to 640
◇	2200	50,000	430 to 530
◁	2200	50,000	625 to 715

Figure 8. - Effect of cooling-air flow ratio on temperature-difference ratio for range of operating conditions. Flight Mach number, 0.8.
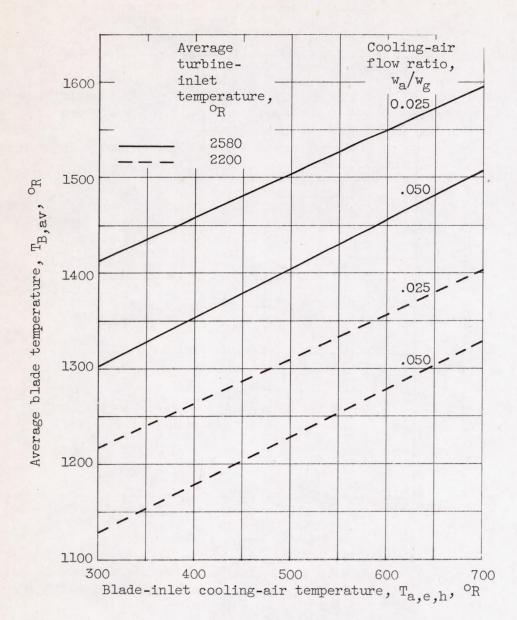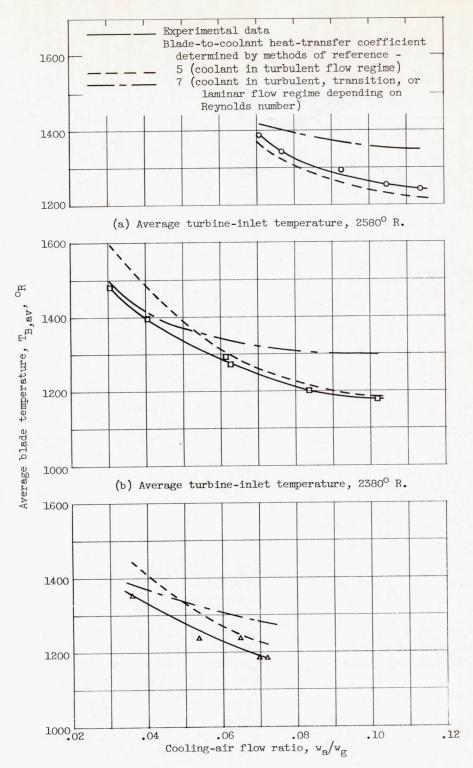
Figure 9. - Effect of blade-inlet cooling-air temperature on average turbine rotor blade temperature at one-third span. Altitudes of 50,000 and 60,000 feet; flight Mach number, 0.8.

(a) Average turbine-inlet temperature, 2580° R.

(b) Average turbine-inlet temperature, 2380° R.

(c) Average turbine-inlet temperature, 2270° R.

Figure 10. - Comparison of analytical and experimental average
turbine rotor blade temperatures at one-third span. Alti-
tude, 60,000 feet; flight Mach number, 0.8.